Aerothermodynamics & Turbulence

8 March 2013

Dr. John D. Schmisseur
Program Officer
AFOSR/RTE
Air Force Research Laboratory

Integrity ★ Service ★ Excellence

Report Documentation Page

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Presented at the AFOSR Spring Review 2013, 4-8 March, Arlington, VA.

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Standard Form 298 (Rev. 8-98)
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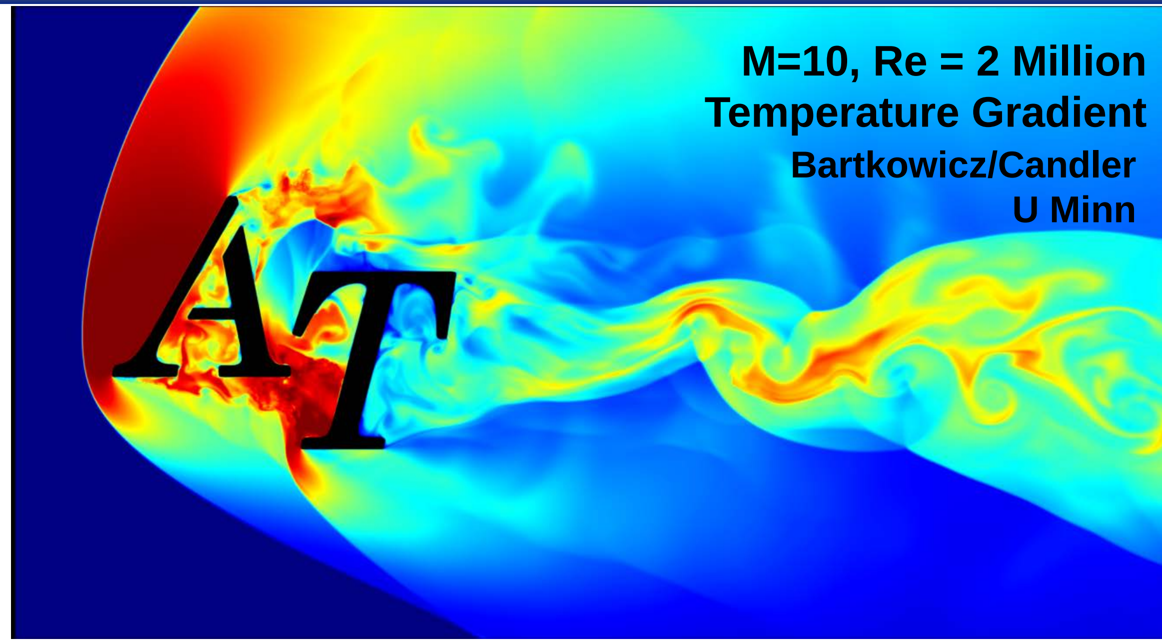
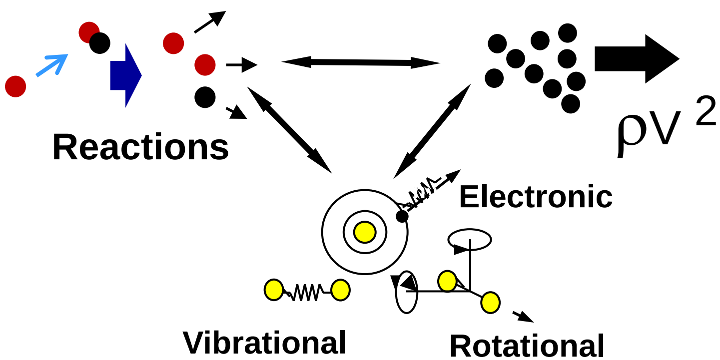
Scientific Foundations of Aerothermodynamics & Turbulence

A&T portfolio exists at the intersection of gasdynamics, thermophysics and chemistry





Goal: *Understand and predict* energy transfer between the kinetic, internal and chemical modes

- *Exploit* this knowledge to shape macroscopic flow behavior

Essential Science for Future High-Speed Capabilities

Strategic Priorities Require Efficient Area Coverage

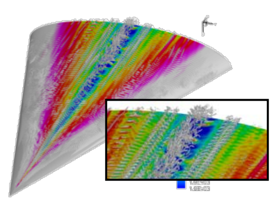
"Pivot to the Pacific"

High-Speed Capabilities Are Potential Game-Changers in response to an Anti-Access/Area Denial threat

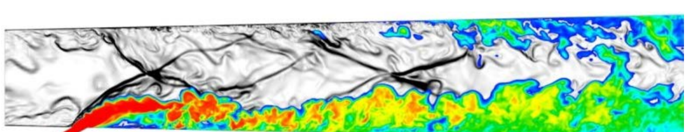
- Survivable
- Responsive
- Efficient – greatly increased area coverage per asset

Advanced Simulation Tools Provide Insight, Reduce Uncertainty

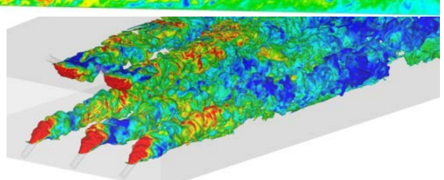
Reduced Uncertainty in Complex Flows



Surface Heat Transfer and Detailed Flow Structure



Fuel Injection in a Scramjet Combustor



Addressing Future Testing Challenges

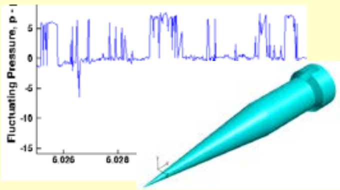
NASA Langley High-Temp Tunnel

- Planned systems expected to be too large for ground test facilities
- Reliable simulations will help "connect the dots"

Leadership and Collaborations

Past

First hypersonic flight data to capture shock interaction unsteadiness



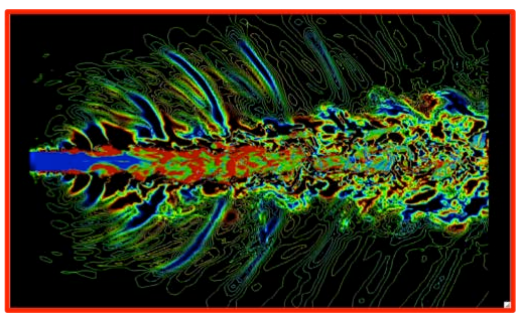
Ongoing

National Hypersonic Foundational Research Plan

Joint Technology Office – Hypersonics
Basic Science Roadmap

Jointly-Sponsored National Hypersonic Science Centers

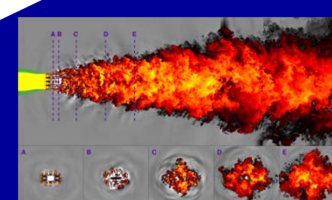
Office of Naval Research



Basic Research for Understanding and Controlling Noise from High-Speed Jets

Assessment of SOA and Future Research Directions

NATO
OTAN



Future

Driving a new scientific paradigm for high-speed flows

Transforming Scope Reflective of Evolving Air Force Responsibilities

Facilitated by FY13 BRI topic: Foundations of Energy Transfer in Multi-Physics Flow Phenomena

Aerodynamics-Driven Focus

Focus on Energy Transfer Mechanisms in Fluids

Legacy Strength
Boundary Layers, Shock Interactions, Aerothermo-dynamics

Thermal Management, Energy Storage and Transport, Plasma Phen.

Atmospheric Energy Propagation, Fluid Phen. In Gas Lasers, Laser-Material Interactions(?)

Other Portfolios

Natural Opportunities for cross-discipline collaboration
- MURI, BRI

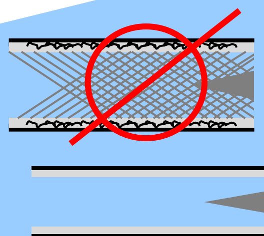
Strategic Vision

Innovation from other disciplines

Goal: Understand, Predict & Exploit Energy Dynamics

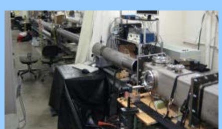
Sustainable Infrastructure for High Mach Science

Facilities



Quiet Tunnels

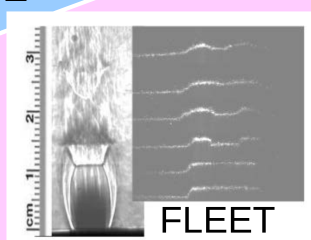
Ludwieg Tubes: Mach 6 at low cost

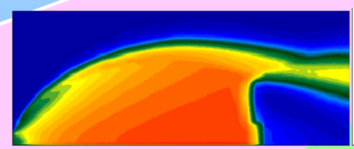


Expansion Tubes – Study Noneq. Flows

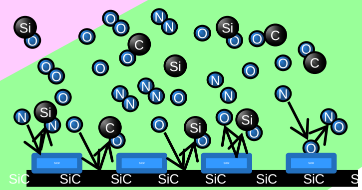
New Insight Into Critical Fine-Scale Phenomena

Diagnostics





VENOM

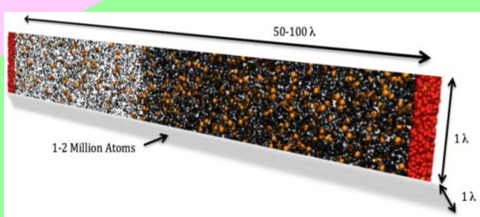


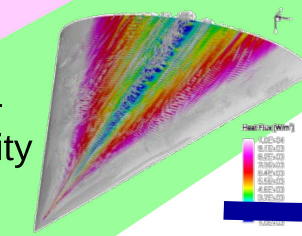
GSI

Towards Model-Free Simulations

Simulations

Accel. MD





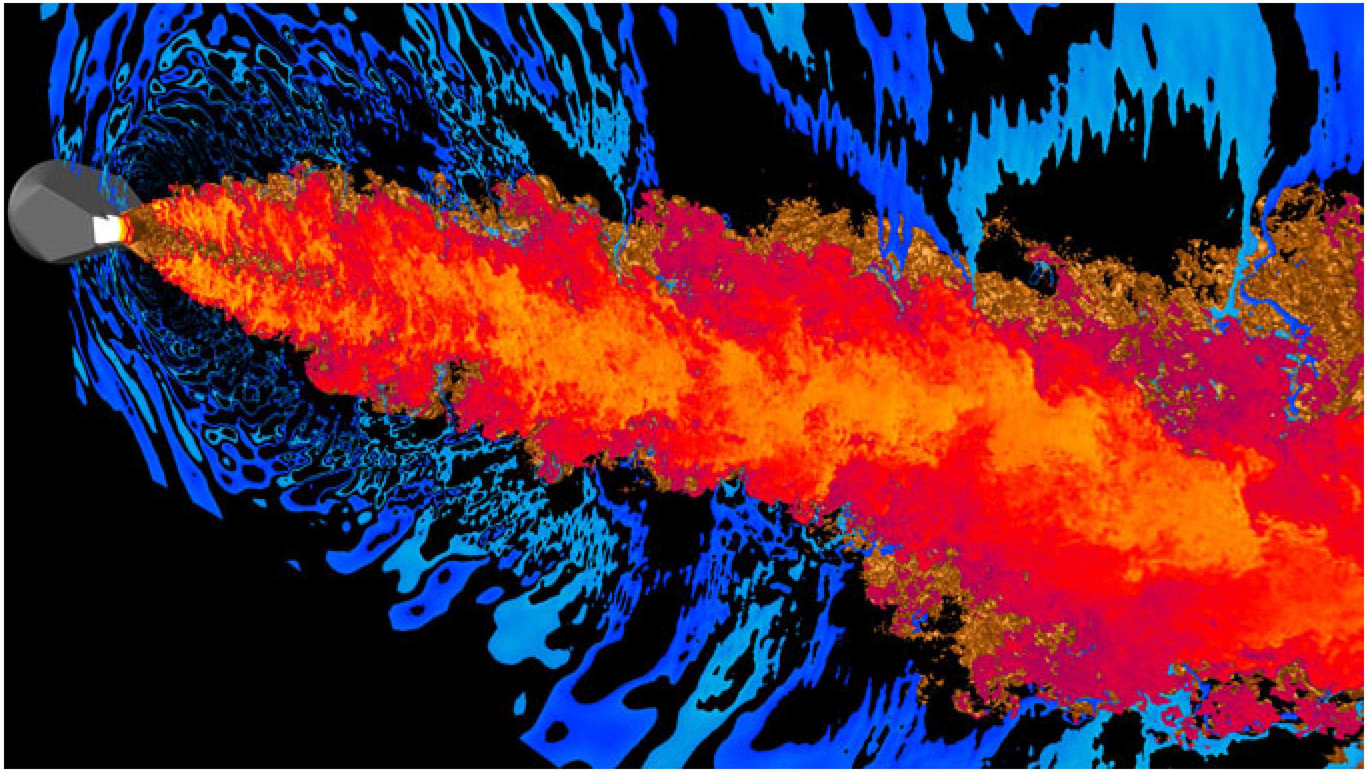
High-Fidelity CFD

Tech Transition

Unprecedented Insight into Critical Molecular- and Micro-Scale Phenomena

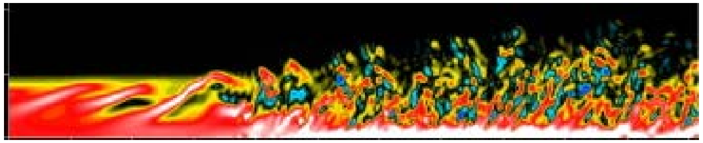
Stanford Researchers Run First Million-Core Simulation at LLNL

AFOSR project investigating jet noise hits milestone with breakthrough simulation



Parviz Moin and Joseph Nichols, Stanford – running CharLES on LLNL Sequoia

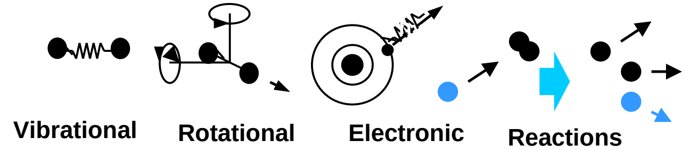
Portfolio Snapshot



Partners

Laminar-Turbulent Transition

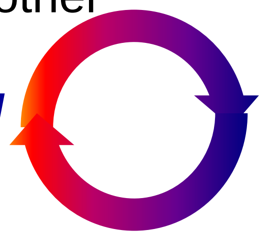
- Major investment area
- Significant progress as result
- Challenge to maintain momentum while balancing investment with other areas



Nonequilibrium Flows

- Emphasis on energy dynamics major new thrust area
- Significant portion of recent investments

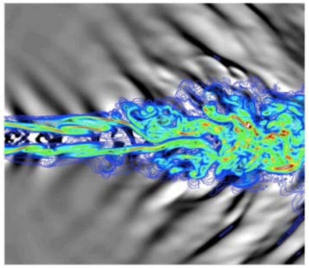
It's all connected

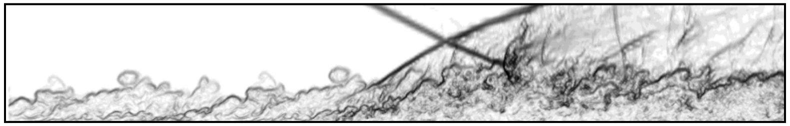


Progress in one area impacts others

Turbulent Physics:

- Roughness and Jet Noise
- Significant investment from other agencies
- OSR investment targets fundamental physics not emphasized elsewhere
- Kinetic energy dynamics is important here





Shock Interactions

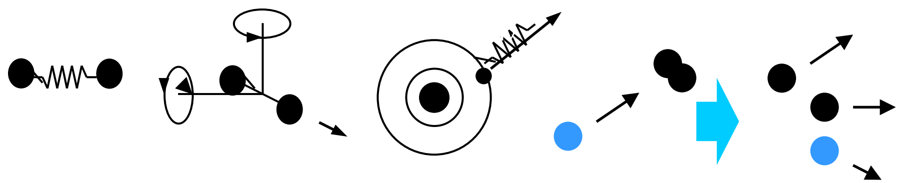
- Critical to planned HS weapons
- Ripe for a <u>hard</u> challenge to inspire innovation
- Aspiring to push this community to the brink soon

Future Portfolio Structure

Portfolio will be split as a result of the New AFOSR Organization

Aerothermodynamics

PO: J. Schmisseur

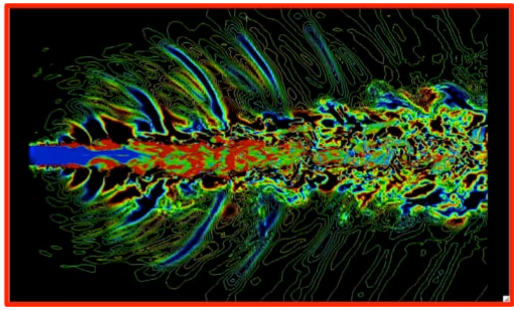


- Intermodal Energy dynamics
  - Kinetic, Internal, Chemical
  - Gas-Surface Interactions
- Excitation Mechanisms
  - Shock Interactions
  - Finite-Rate Processes

In Energy, Power & Propulsion

Turbulence & Transition

PO: TBD



- Kinetic Energy dynamics
  - Instability growth and competition
  - Physics of Turbulence
- Impact of Boundary and Initial Conditions
  - Surface Roughness
  - Inflow Disturbance Effects

In Dynamical Systems & Controls:

Accomplishments & Transitions

Current PI Accomplishments

- Members of the NAE (6)
- NSSEFF Fellow
- DoD Advisory Boards
  - AF SAB
  - JASON
  - Def. Studies Group
- PECASE (2)
- NSF CAREER (4)
- OSR Young Investigator (4)

Our Alumni

- AIAA Past President (2)
- AF Chief Scientists (2)
- Prior PM: Dr. S. Walker

Candler, Schneider and Miles Recognized with AIAA Awards

Examples of Recent Tech Transitions

- 6 Students working at AFRL
- Purdue M6 Quiet Tunnel named critical national T&E resource
- *Lead* SME Consultants for HTV-2, CPGS
- Performed critical analysis for X-51 post-flight 2 investigation
- Transitioned STABL code to 25 org.
  - T&E version funded by TRMC
- Transitioned US3D CFD to 14 org.
  - AFRL, NASA, Boeing, LM, UTRC …
- Provided algorithm for accelerated chemistry sims in CFD to AFRL/RV
- Supported DARPA, MDA, Sandia, …

Outline

- Objectives, Challenges, Opportunities and Impact
- Portfolio Description
- Research Highlights
  - Laminar-Turbulent Transition
  - Energy Transfer Mechanisms
- Research Directions
- Summary

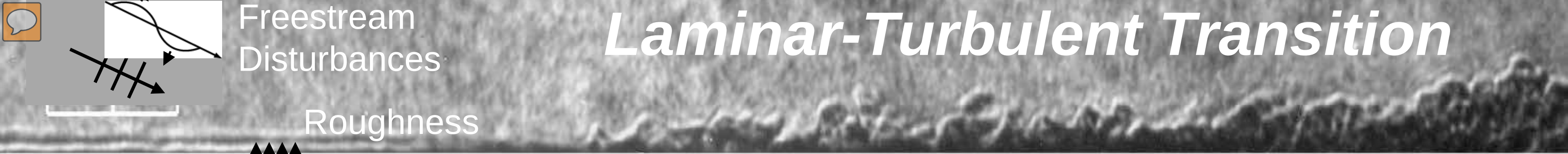
Innovative approach to evolving AF needs

Extensively coordinated with other agencies

Exciting Science

- Leveraging advancements in numerics and diagnostics
- Importing expertise from other disciplines
- Unprecedented insight into fundamental processes

Laminar-Turbulent Transition



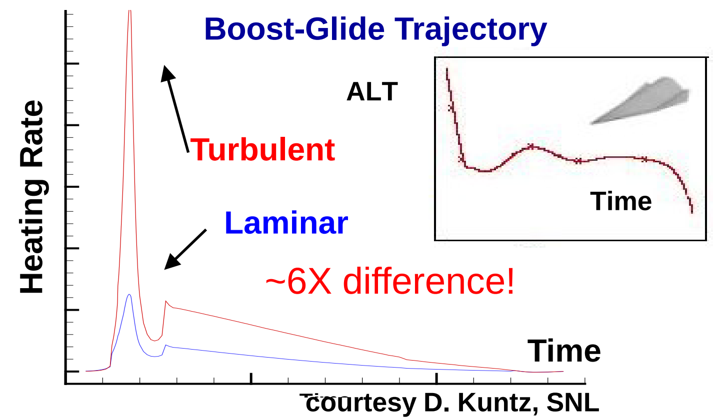
Disturbances trigger instabilities which drive breakdown to turbulent state

Image: Hornung, Cal Tech

Challenges – understand K.E. Dynamics

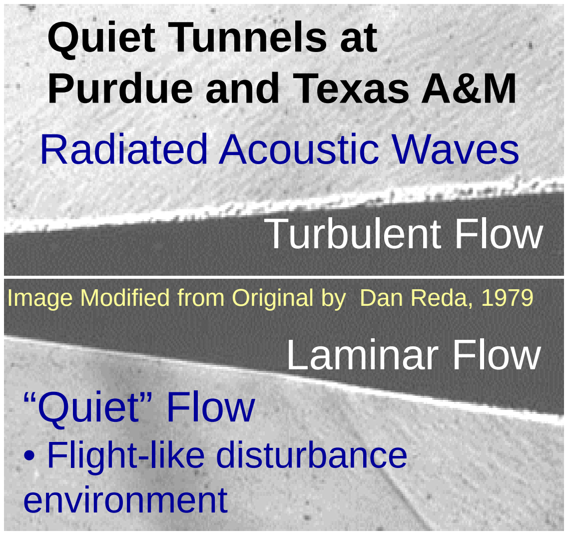
- Dynamics occur at the microscale
  - Key instability dynamics occur at 10^{-6} of mean
- Process is a "race" between competing growing instabilities
- Nonlinear interactions play critical role

Design Driver for High-Speed Systems

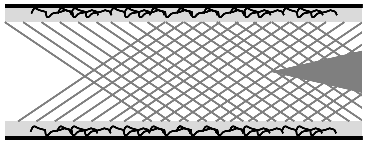


courtesy D. Kuntz, SNL

Key Capability Advancements



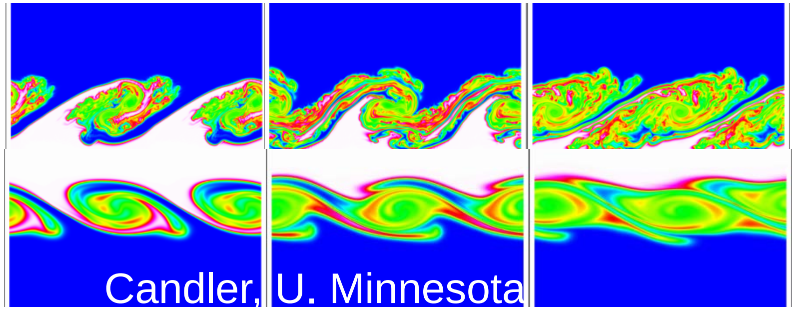
Conventional tunnels: noise corrupts transition experiments



Quiet tunnels: allow natural disturbance growth – "flight-like"

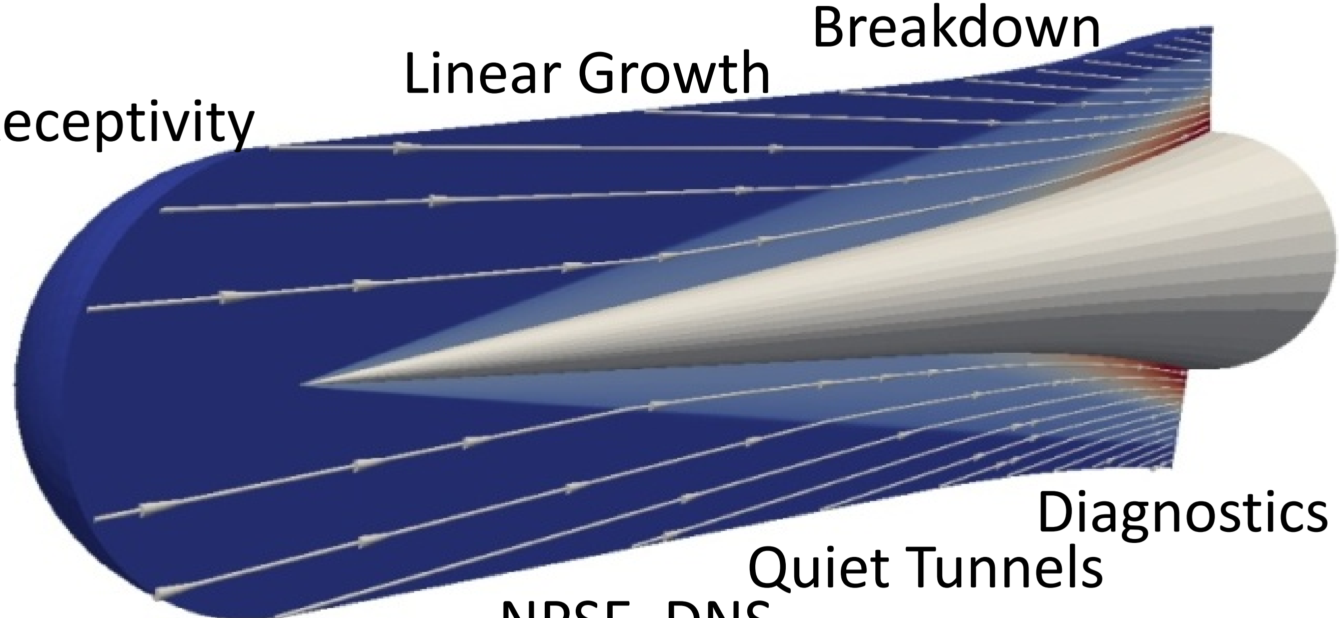
Advanced Numerical Methods

- Stability analysis – Texas A&M, Minnesota
- High Resolution @ Scale - Minnesota

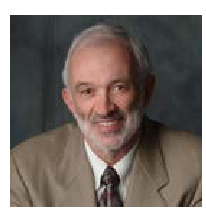


Driving Scientific Progress

National Hypersonic Science Center: *Integrating the best and brightest to enhance physics-based understanding and prediction of transition*



3 NAE Members
16 Fellows
2 NRC, 3 NATO
> 80 students
> 140 publications
2 Annual Review Articles
Many external meaningful collaborations

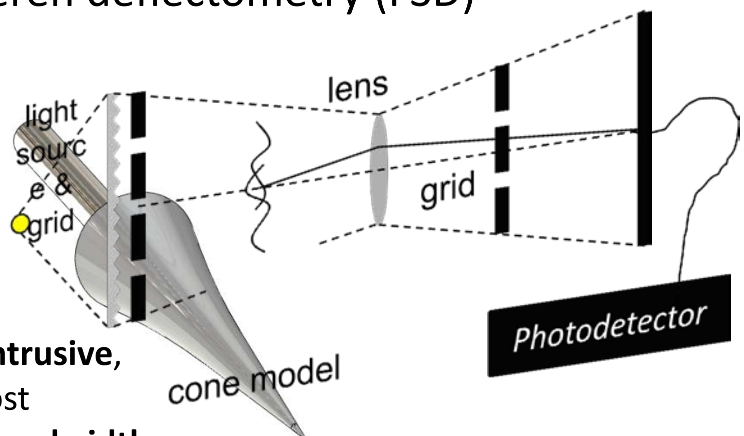


New Insight Into Critical Physics

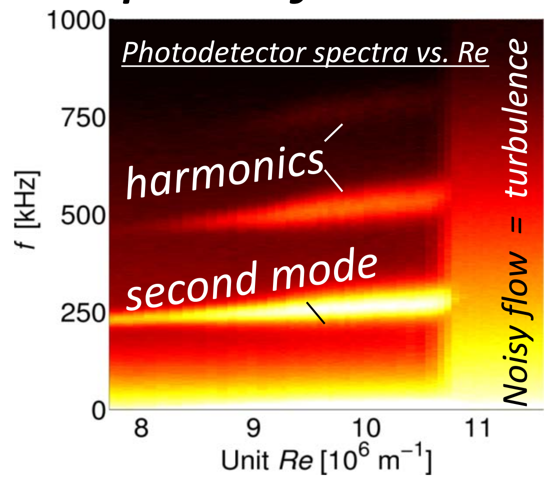
Second-mode nonlinear interactions quantified

Texas A&M Mach 6 Quiet Tunnel

- New optical measurements via focused schlieren deflectometry (FSD)

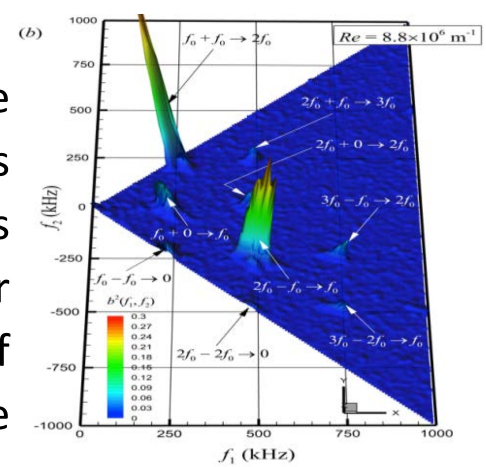


- **Non-intrusive,**
- low-cost
- **High bandwidth** (1 MHz)



Sensitive FSD spectra reveal harmonics of second mode

Bicoherence analysis identifies nonlinear interactions of second mode and harmonics



Quantified second-mode nonlinear interactions enable identification of critical modes in transition process

Hofferth, J.W., Humble, R.A., Floryan, D.C., and Saric, W.S.
AIAA Paper No. 2013-0378.

W. Saric, NAE
Distinguished Professor

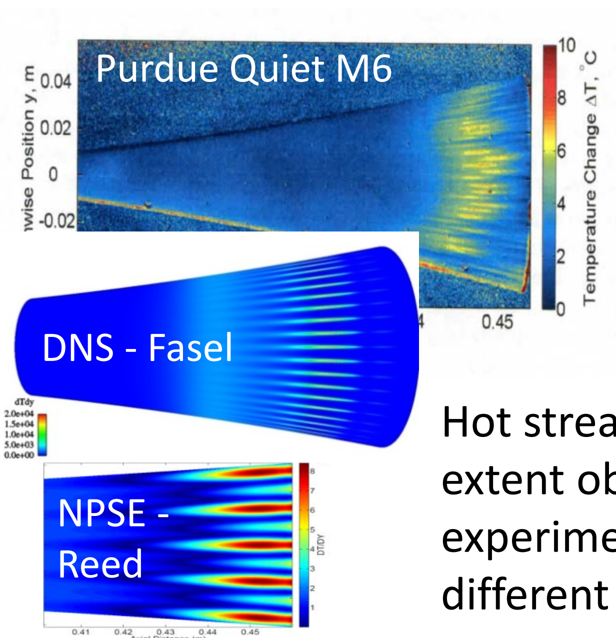
Jerrod Hofferth
Ph.D. Candidate

Helen Reed
Professor
“NPSE Validation”

New Insight Into Critical Physics

Three-stage breakdown model provides new insight into hypersonic transition

Explains overshoot in skin friction and heat transfer

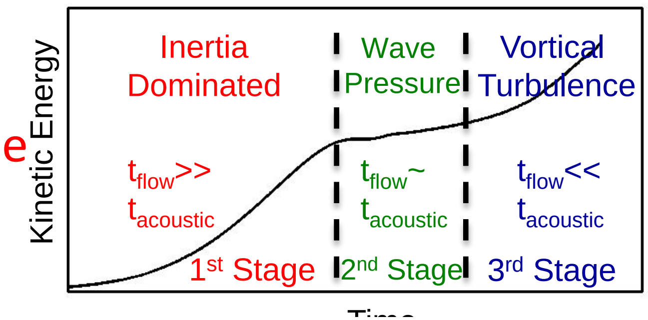


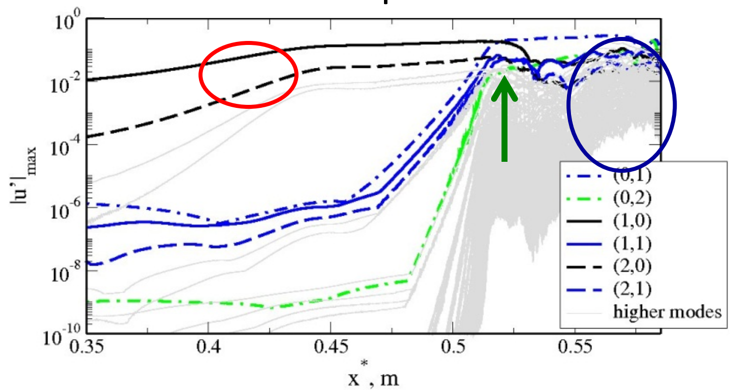
Initial rise in friction from large amplitude primary wave

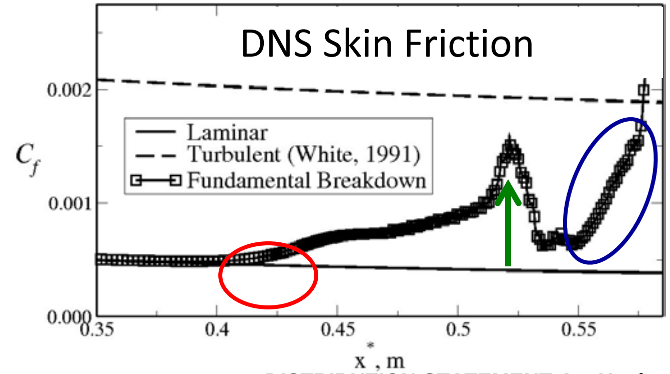
Saturation of primary wave

Steeper rise as all higher modes grow nonlinearly

Hot streaks of limited extent observed in DNS, experiment, NPSE for 3 different geometries







H. Fasel
Professor

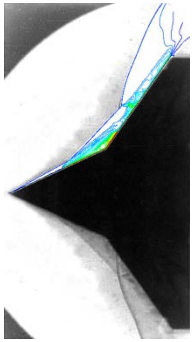
S. Girimaji
Professor

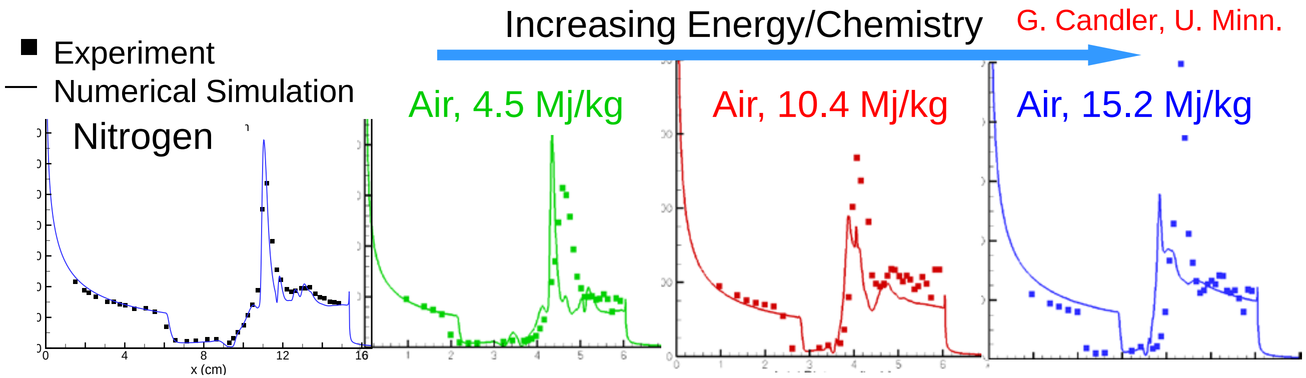
H. Reed
Professor

Bertsch,R. L. and Suman,S. and Girimaji,S. S. Physics of Fluids, Vol. 24, No. 12, 2012.

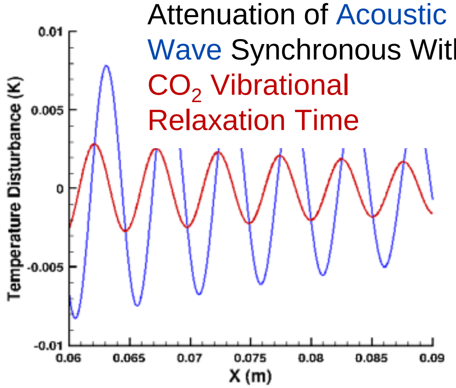
Establish and Exploit A Fundamental Understanding of Energy Transfer in Flows

Predictions Fail as Chemical Complexity Increases

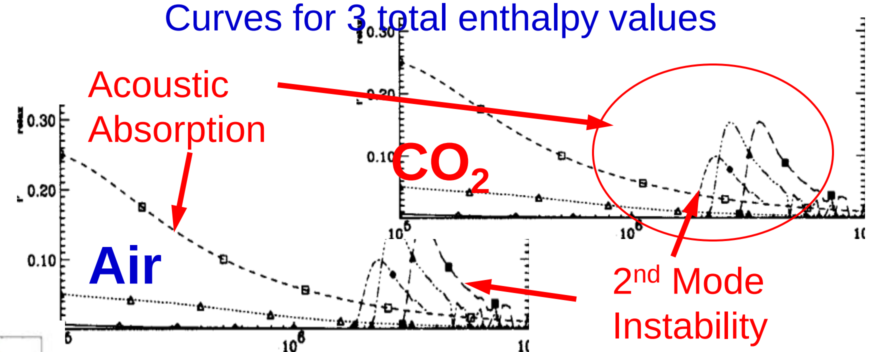




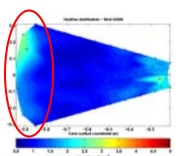
Control Energy Transfer to Tailor Macroscopic Flow



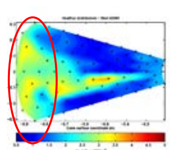
For CO_2 internal energy and acoustic instability modes overlap



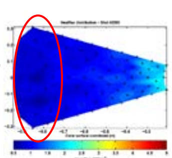
No Injection



Argon at 12 g/s



CO2 at 12 g/s



Ar injection promotes transition, CO2 inhibits transition

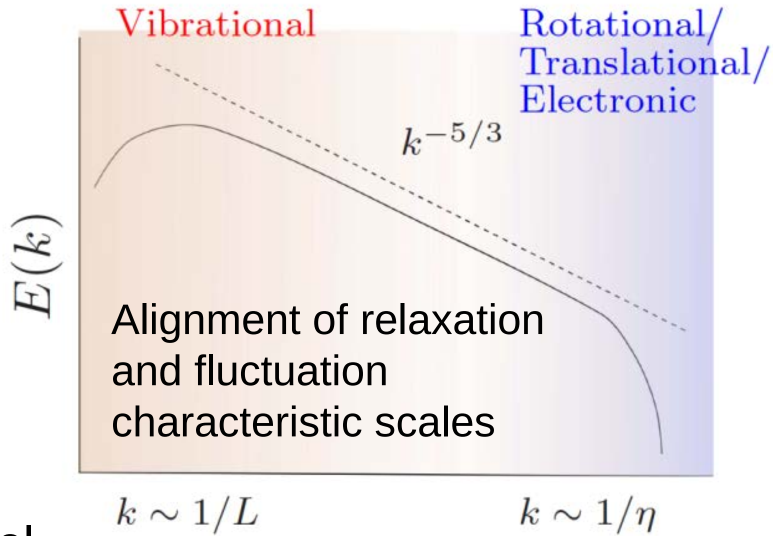
Key to Progress is the Understanding and Accurately Modeling the Rate-Dependent Energy Transfer Mechanisms

2013 Basic Research Initiative

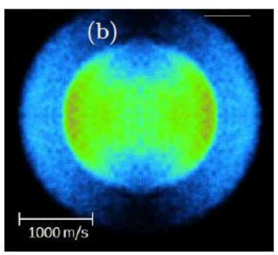
Foundations of Energy Transfer in Multi-Physics Flow Phenomena

Non-equilibrium effects on turbulent flows:

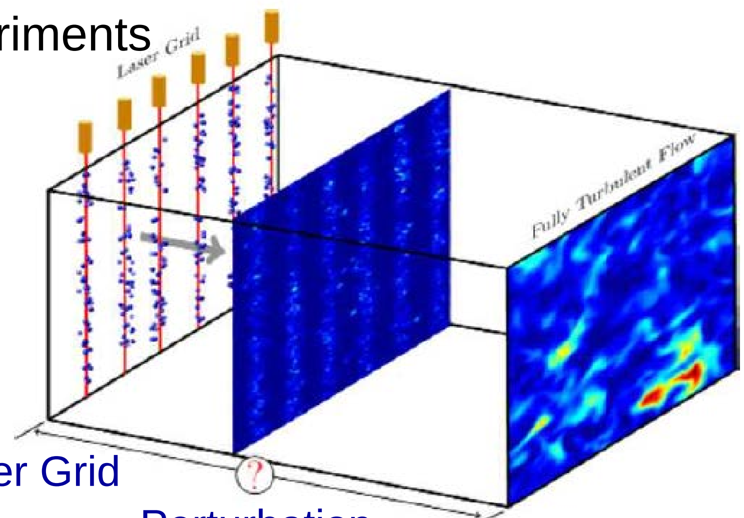
Can turbulence be shaped via coupling with internal energy transitions?



Utilizing massively large-scale DNS, molecular dynamics simulations and novel laser based experiments



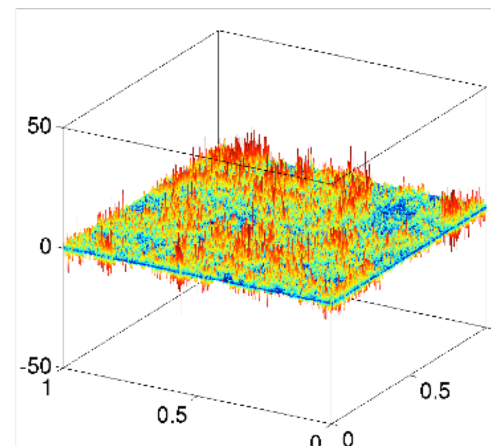
Laser-Generated Flow Perturbation



Laser Grid

Perturbation Pattern

Turbulence



DNS: Velocity gradients from shock turbulence interactions

D. Donzis
Assist. Professor

R. Bowersox
Professor

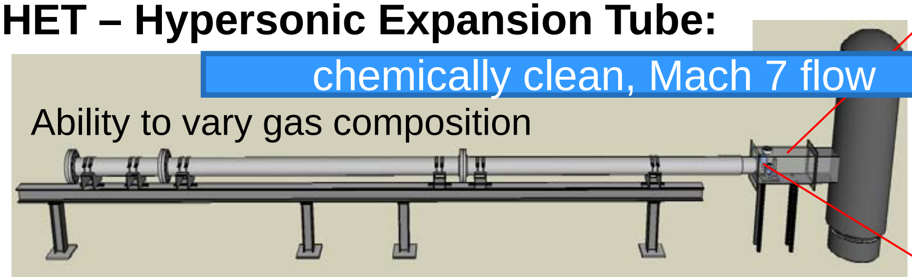
S. North
Professor

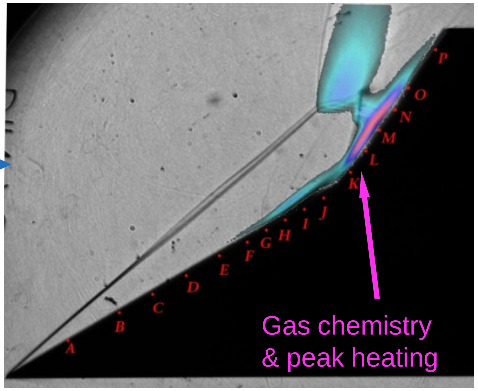
W. Haze
Professor

Establish and Exploit A Fundamental Understanding of Energy Transfer in Flows

Joint experiments and simulations reveal new insight into gas chemistry effects

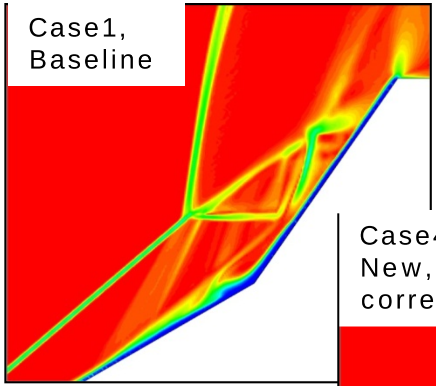
HET – Hypersonic Expansion Tube:

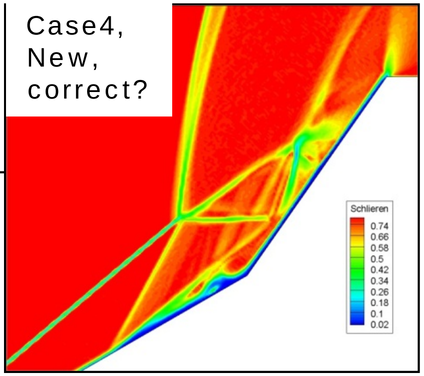




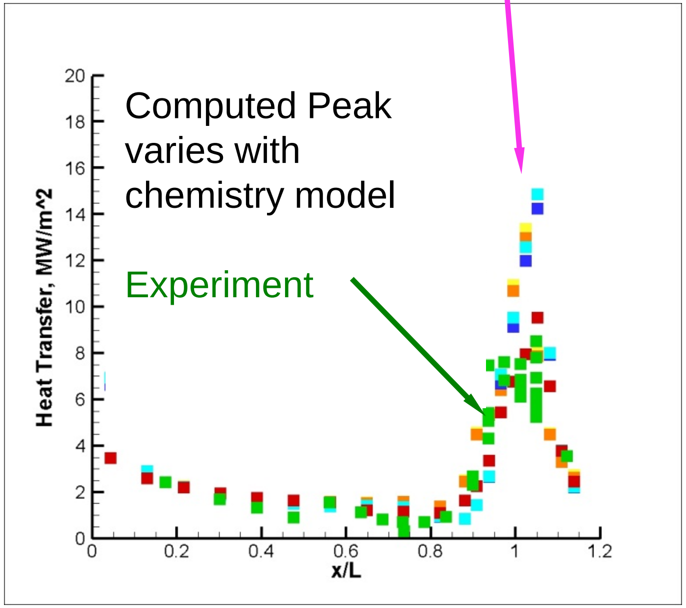
Joanna Austin
U. Illinois
- AFOSR YIP
- NSF CAREER

Simulated shock structure varies with surface chemistry model





"Study of shock-shock interactions for the HET facility double wedge configuration using a particle approach", To be presented San Diego, June 2013, AIAA Fluid Dynamics



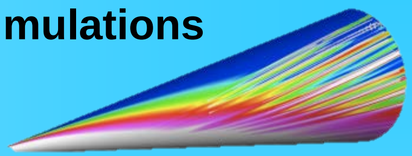
Deborah Levin
Penn State
- JTHT Assoc. Ed.

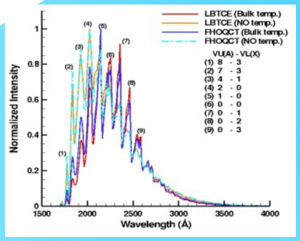
MURI: Fundamental Processes in High-Temperature Hypersonic Flows

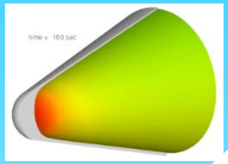
MURI addresses scale-up of knowledge from molecular potential to nonequilibrium flow over a full-scale body

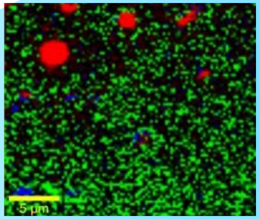
- Integrates contributions from chemistry, material science, and aerothermodynamics
- Coordinated simulations and experiments

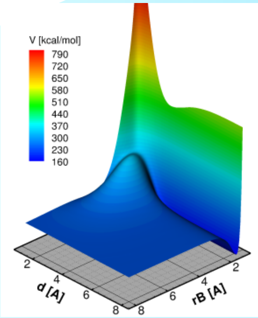
Accurate Hypersonic Simulations

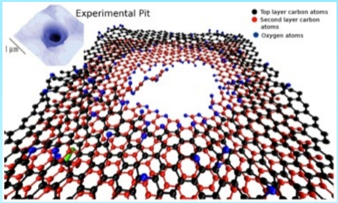




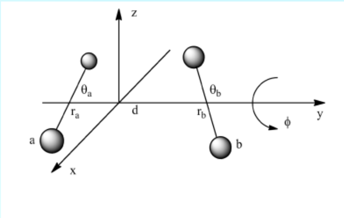








Quantum Chemistry



PI - Graham Candler

Paul DesJardin, Matt MacLean

Debbie Levin

Erica Corral

Tim Minton

Tom Schwartzentruber

Adri van Duin

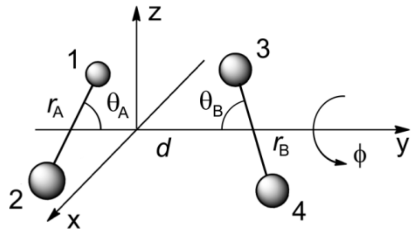
Dan Kelley

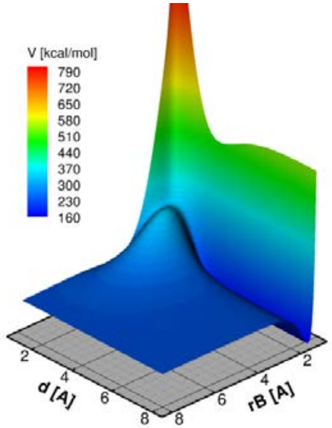
Don Truhlar

- 14 grad students
- 10 post-docs
- 2 undergrad
- 18 articles
- 18 conference papers

Nanoscale: Quantum Chemistry / MD of Critical Processes

Quantum chemistry advances gas-phase and gas surface interaction simulations

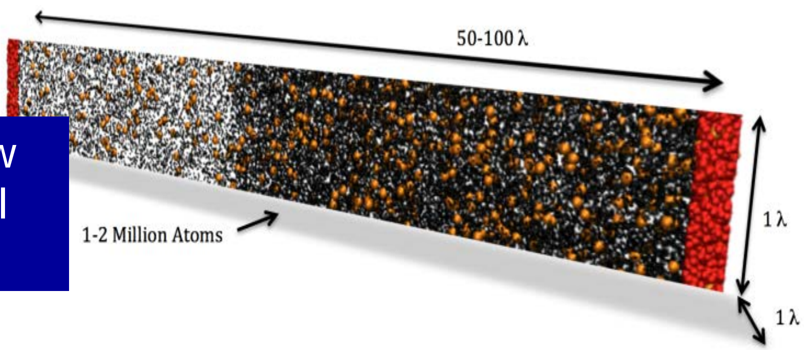




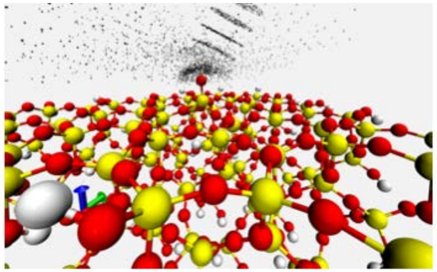
Relevant N_4, O_4, N_2O_2 potential energy surfaces calculated from interatomic potential

First simulation of shock wave using only atomic potentials as model

MD + New Numerical Scheme



New gas-surface interaction model consistent with physical chemistry



Rate	Rate Equation	Rate constant (k_i)	units
r_1^f	$k_1^f[O][E_s]$	$(\bar{c}_O/4) \times (2\pi r_c^2) \times (A_1^f e^{-E_1^f/(K_BT)})$	m^3/s
r_1^r	$k_1^r[O_s]$	$A_1^r e^{-E_1^r/(K_BT)}$	$1/s$
r_2^f	$k_2^f[O][O_s]$	$(\bar{c}_O/4) \times (2\pi r_c^2) \times (A_2^f e^{-E_2^f/(K_BT)})$	m^3/s
r_2^r	$k_2^r[O_2][E_s]$	$(\bar{c}_{O_2}/4) \times (2\pi r_c^2) \times (A_2^r e^{-E_2^r/(K_BT)})$	m^3/s
r_3^f	$k_3^f[O][O_s]$	$(\bar{c}_O/4) \times (2\pi r_c^2) \times (A_3^f e^{-E_3^f/(K_BT)})$	m^3/s
r_3^r	$k_3^r[O_{2s}]$	$A_3^r e^{-E_3^r/(K_BT)}$	$1/s$
r_4^f	$k_4^f[O][O_{2s}]$	$(\bar{c}_O/4) \times (2\pi r_c^2) \times (A_4^f e^{-E_4^f/(K_BT)})$	m^3/s
r_4^r	$k_4^r[O_2][O_s]$	$(\bar{c}_{O_2}/4) \times (2\pi r_c^2) \times (A_4^r e^{-E_4^f/(K_BT)})$	m^3/s
r_5^f	$k_5^f[O_2][E_s]$	$(\bar{c}_{O_2}/4) \times (2\pi r_c^2) \times (A_5^f e^{-E_5^f/(K_BT)})$	m^3/s
r_5^r	$k_5^r[O_{2s}]$	$A_r^5 e^{-E_5^r/(K_BT)}$	$1/s$

Table 4: Rate Constants and functional forms

Dr. Thomas Schwartzentruber
AFOSR *Young Investigator Award* (2009)

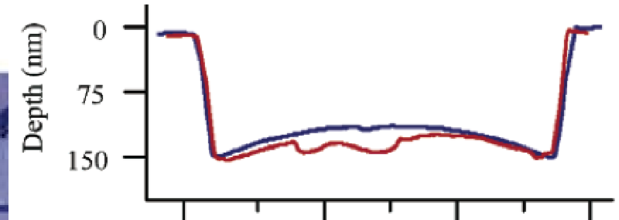
Dr. Adri van Duin

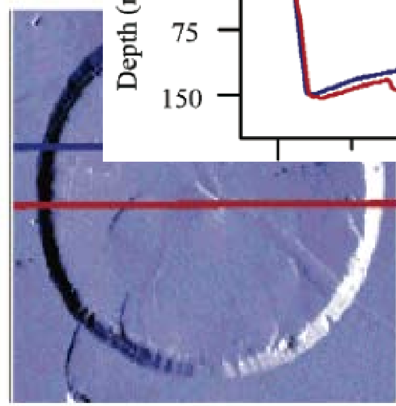
Kulkarni, Truhlar, Srinivasan, van Duin, Norman, Schwartzentruber: J Phys. Chem. (2012)

Microscale: Highly Oriented Pyrolitic Graphite Oxidation

Coordinated experiments and simulations: bridging computational chemistry to macroscopic ablation experiments

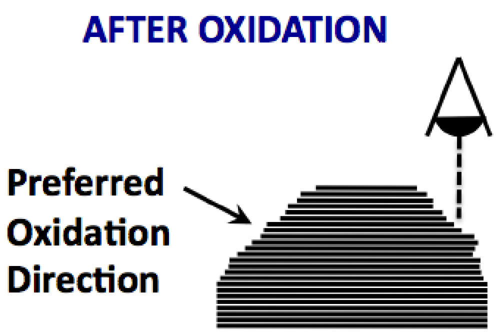
HOPG is a well-characterized form of carbon: planar



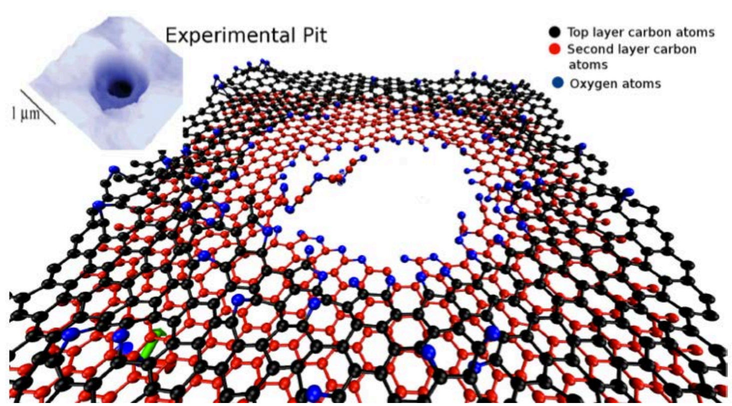


(1) Oxidation by molecular beam

(2) Oxidation in furnace



(3) MD at molecular beam conditions



Graphitic layers preferentially oxidize at edges due to open bond sites

Prof. Thomas Schwartzentruber

Prof. Erica Corral

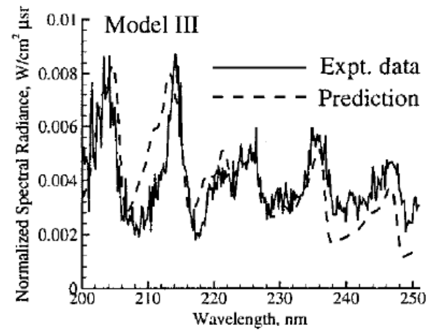
Prof. Tim Minton

Prof. Adri van Duin

Poovathingal, Schwartzentruber, Srinivasan, van Duin: J. Phys. Chem. (submitted)

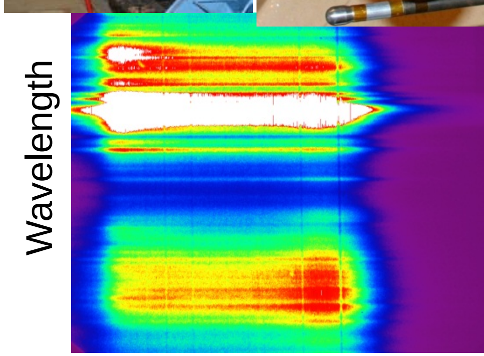
Macroscale: Spectral Measurements of Shocklayer Emission

Integrated Flight and Ground Test Data Provide Unique, Detailed, and Unequivocal Data for Model Validation



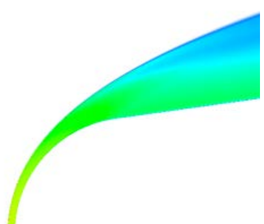
BSUV Flight Data: UV Emission from Sounding Rocket Nose: Bose, Candler, Levin (1998)

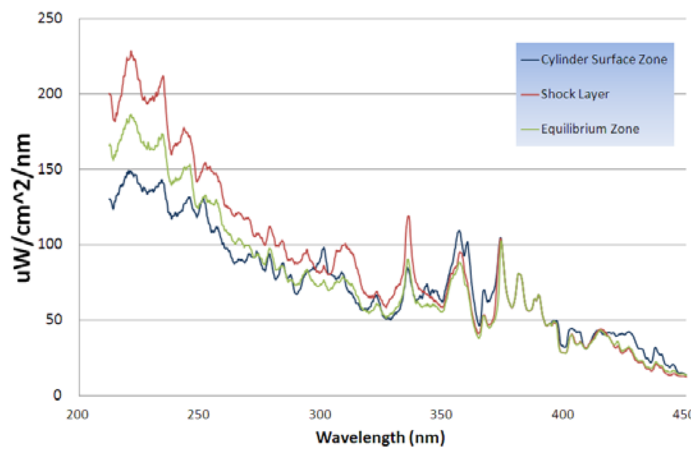
UV Radition Measured in LENS XX –Expansion Tunnel



surface **shock**

Model effectiveness assessed from comparison of spectra from tunnel measurements, flight data, CFD and theory





Prof. Graham Candler
U. Minnesota

Prof. Paul Desjardin
U. Buffalo

Prof. Deborah Levin
Penn State

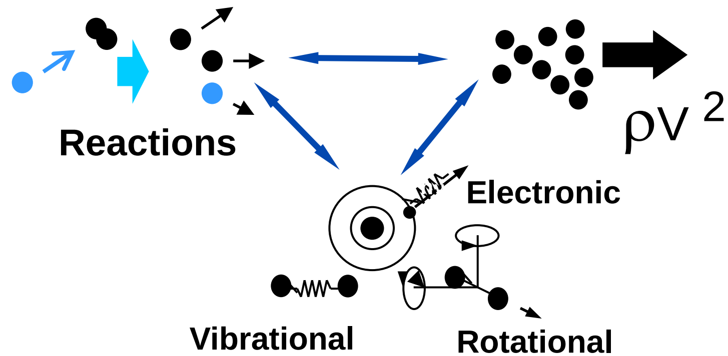
Parker, MacLean, Dufrene, Holden, Desjardin, Weisberger, Levin: AIAA-2013-1058

Outline

- Objectives, Challenges, Opportunities and Impact
- Portfolio Description
- Research Highlights
  - Laminar-Turbulent Transition
  - Energy Transfer Mechanisms
- Research Directions → • Where we're going
- Summary

2013 Basic Research Initiative

Foundations of Energy Transfer in Multi-Physics Flow Phenomena



Establish the multidisciplinary scientific foundation for innovative approaches to *inherent* flow control

- Identify fundamental processes
- Exploit energy transfer in shaping macroscopic flow behavior

Bridging Multiple Portfolios

- Aerothermodynamics and Turbulence
- Energy Conversion and Combustion Sciences
- Molecular Dynamics and Theoretical Chemistry
- Flow Interactions and Control
- Plasma and Electroenergetic Physics

RTE

RTA

RTB

Emphasized projects that bridged interests of at least two of the participating portfolios

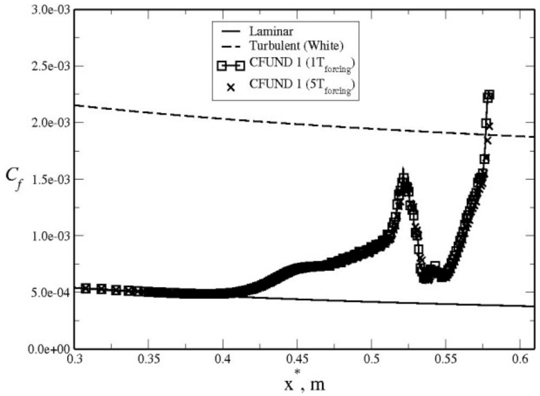
Opportunity to Pick Up New Ideas from Other Disciplines

Upcoming Emphasis Area: Conjugate Gas-Surface Interactions

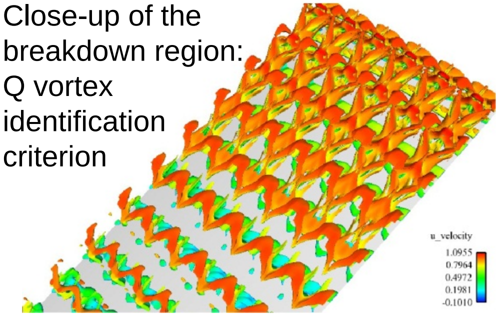
"…the crosshatch patterns degenerate to scallop patterns. For some materials, such as graphite, the degeneration process is so rapid that the initial crosshatch pattern is generally indiscernible."

Grabow & White, AIAA J, 13, 5

- Pattern is material-dependent
- Kinetic effect – occurs at low temp



Close-up of the breakdown region: Q vortex identification criterion

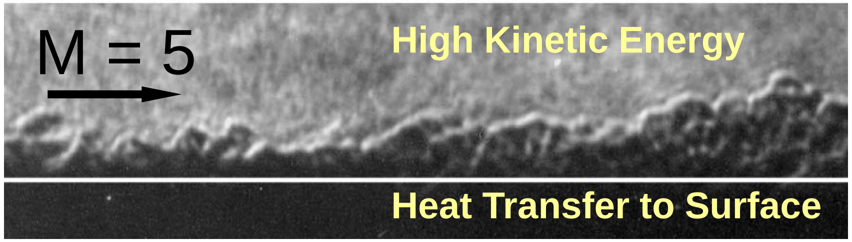


Does the 3-Stage Breakdown Model Developed by the NHSC –Transition Team Contribute to the Ablation Pattern Above?

- How do the flow structure and material response couple?

We now have the tools to take on the challenge of complex, coupled flow surface interactions

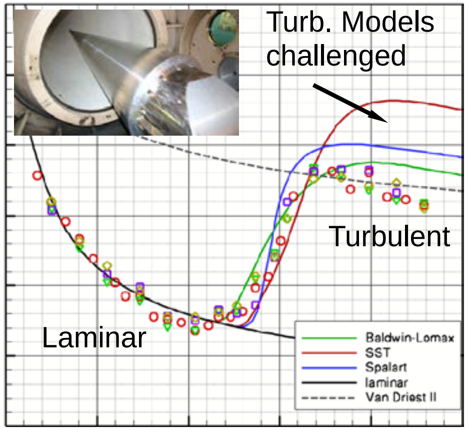
Upcoming Emphasis Area: Highly-Distorted Turbulence



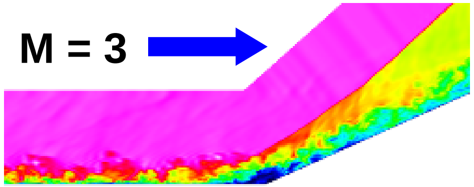
Boundary Layer: Viscous diffusion of kinetic energy into heat

If this is tough…

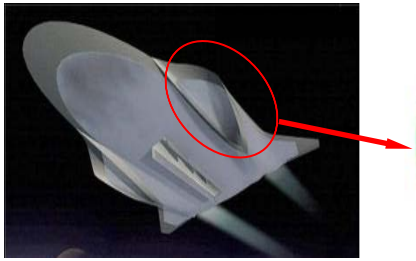
Heat transfer prediction remains a challenge for high-speed boundary layers

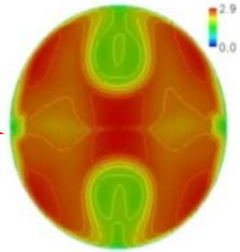


Planned High-Speed Systems will have Highly-Distorted Boundary Layers



Shock/Boundary Layer Interaction: Extreme loads at separation and reattachment

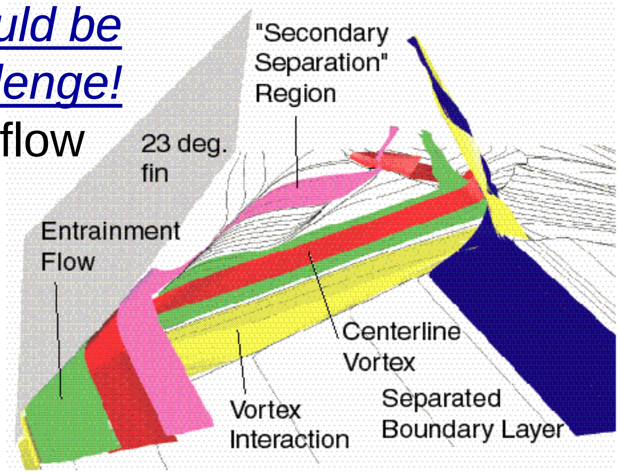




Inlet Distortion Effects Efficiency

… this should be a ***real*** *challenge!*

Significant flow distortion occurs in 3-D SBLIs



Utilize full-spectrum of diagnostic and simulation capabilities to explore energy dynamics in highly-distorted turbulent flows

Summary

- Objectives, Challenges, Opportunities and Impact
- Portfolio Description
- Research Highlights
  - Laminar-Turbulent Transition
  - Energy Transfer Mechanisms
- Research Directions
- Summary

- **World-leading scientific research with game-changing impact**
- **Evolving with expanding AF areas of responsibility**
- **Leveraging contributions from other disciplines**
- **Unprecedented insight into fundamental processes**
- **Future directions are scientifically challenging while relevant**

2013 AFOSR SPRING REVIEW
2307/A Aerothermodynamics and Turbulence

NAME: John D. Schmisseur

Aerothermodynamics &Turbulence

BRIEF DESCRIPTION OF PORTFOLIO:

Identify, Model and Exploit *critical physical phenomena* in turbulent and high-speed flows

- emphasis on energy transfer

Sole US basic research program in this area

SUB-AREAS IN PORTFOLIO:

- Boundary Layer Physics
- Shock-Dominated Flows
- Gas Thermophysics
    - Gas-Surface Interactions
- Turbulence and Transition

Partners

Sandia National Laboratories

National Hypersonic Foundational Research Plan → Joint Technology Office - Hypersonics

Australian Government Department of Defence Defence Science and Technology Organisation → HIFiRE

NATO OTAN R&T Organization — **Assessment of SOA and Future Research Directions**

ONR Office of Naval Research — NASA — Jet Noise

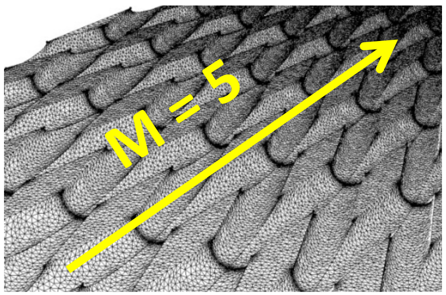
Arnold Engineering Development Center — DARPA — Tech Transition

Exploring Nonequilibrium Turbulence

Roughness Pattern Reduces Turbulence Near Surface:

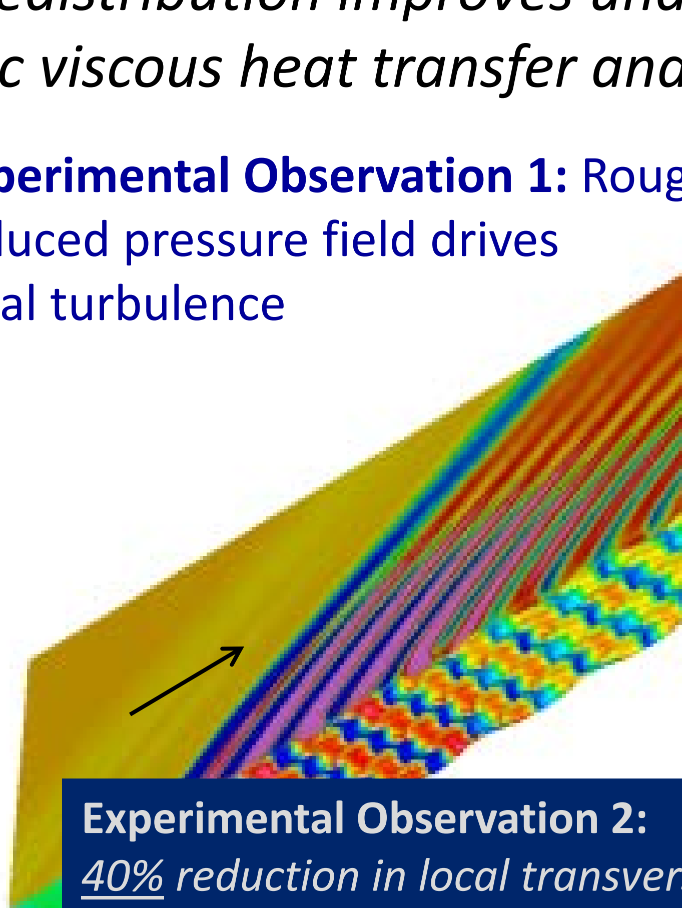
Unraveling energy redistribution improves understanding and control of hypersonic viscous heat transfer and drag

R. Bowersox
Professor

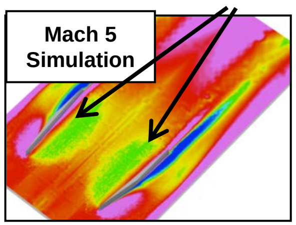


Cross-hatched roughness pattern similar to ablated surfaces

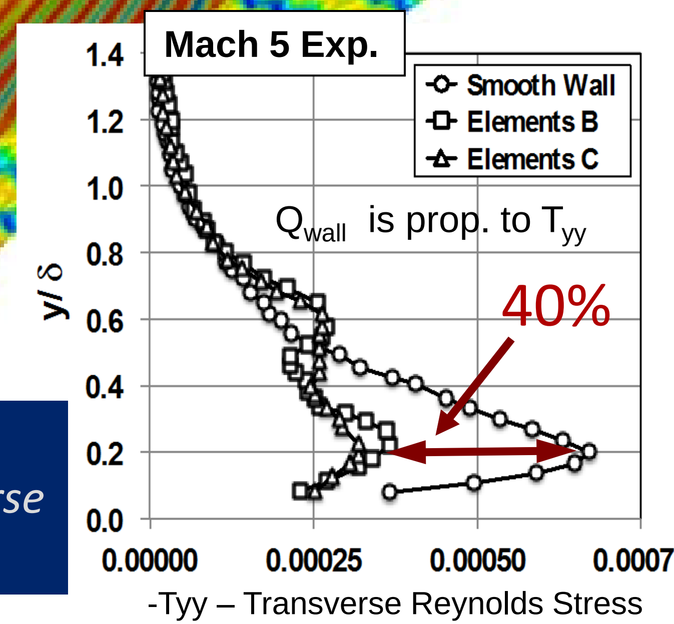
Experimental Observation 1: Roughness induced pressure field drives local turbulence



RANS Simulations: Tailored pressure gradient reduces local turbulence



Experimental Observation 2:
<u>40%</u> reduction in local transverse stresses → Reduced heat flux



Tichenor,* N., Humble, R. and Bowersox, R., in-print *Journal of Fluid Mechanics,* 2013.
Bowersox, R., "*Journal of Fluid Mechanics*, Vol. 633, August 2009, pp. 61-70.
Ekoto*, I., Bowersox, R., Beutner, T. and Goss, L., "*Journal of Fluid Mechanics*, Vol. 630, July 2009, pp. 225-265.

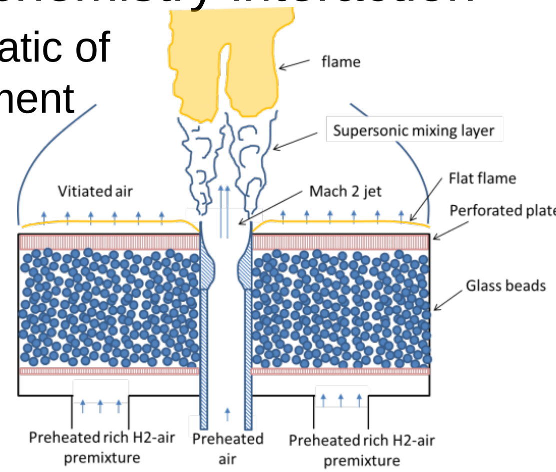
Foundations of Energy Transfer in Multi-Physics Flow Phenomena

New Control Strategies for Supersonic Combustion

Non-equilibrium effects on turbulence chemistry interaction

Can ro-vibrational non-equilibrium effectively transfer energy from thermal to mechanical or chemical modes in high speed turbulent flow?

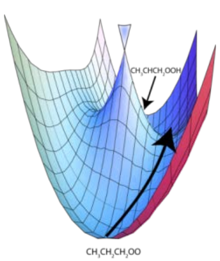
Schematic of experiment



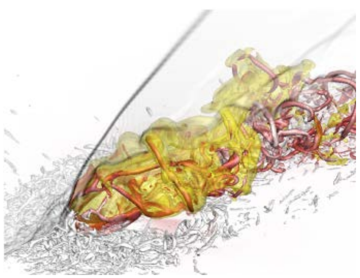
THE UNIVERSITY OF TEXAS AT AUSTIN

Profs. Philip Varghese, Noel Clemens, Venkat Raman – UT Austin
Prof. Wes Allen – U Georgia

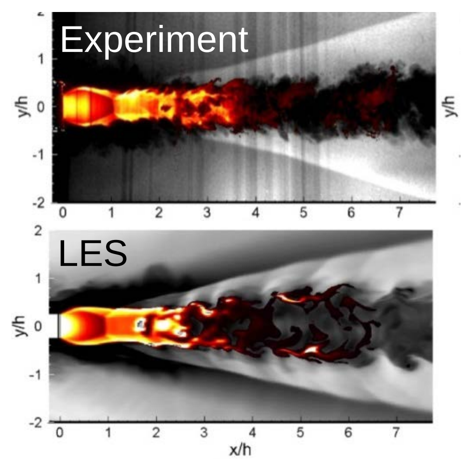
Integrating advanced laser diagnostics with innovative computational chemistry



Potential Energy Surface – helps determine reaction rates



Detailed flow simulations of ethylene jet in cross flow using accurate rates



Kr PLIF + CO_2 Fog

S. Kim, P. Donde, V. Raman, K. Lin, C. Carter, AIAA paper 2012-482, 2012

R. Burns, H. Koo, N. Clemens, V. Raman, AIAA paper 2011-3936, 2011